

Black hole neutron star coalescence as a source of gamma-ray bursts

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Abstract.

We present the results of hydrodynamic (SPH) simulations showing the coalescence of a black hole with a neutron star to be a promising theoretical source of short duration gamma-ray bursts. The favorable features of the process include rapid onset, millisecond variability, a duration much longer than the dynamical timescale, and a range of outcomes sufficient to allow variety in the properties of individual gamma-ray bursts. Interestingly, the process of coalescence differs rather markedly from past predictions.

INTRODUCTION

The coalescence of a tight binary composed of two extremely compact objects (two neutron stars or one neutron star and a black hole) has been suggested as a possible source of cosmological GRBs [9]. In the black hole–neutron star scenario, the neutron star was expected to be tidally disrupted and to form a long-lived accretion torus around the black hole, thus powering a relativistic fireball that produces the observed GRB. Our aim is to investigate the outcome of the coalescence from the standpoint of the hydrodynamics, and explore how the initial mass ratio and the degree of tidal locking in the binary affect the final outcome. In particular, it is of great interest to determine if the neutron star is completely disrupted in a single encounter and if a baryon-free axis persists throughout the process.

NUMERICAL METHOD AND ASSUMPTIONS

For the calculations presented here we have used a three dimensional newtonian smooth particle hydrodynamics [8] code [5]. The neutron star is modeled via a stiff polytropic equation of state, i.e $P = K\rho^\Gamma$, with $\Gamma = 3$. The unperturbed radius of the spherical neutron star is $R_{NS} = 13.4\text{km}$ and its mass is $M_{NS} = 1.4 \text{ M}_\odot$. The black hole is modeled as a Newtonian point mass with an absorbing boundary

at the Schwarzschild radius $r = 2GM_{BH}/c^2$. Any particle in the simulation that crosses this boundary is absorbed by the black hole and its mass is added to that of the black hole. For the different simulations we vary the initial mass ratio of the binary $q = M_{NS}/M_{BH}$ by adjusting the mass of the black hole only.

RESULTS

Tidally locked binaries

For any value of the mass ratio one can construct tidally locked initial configurations that are in equilibrium [10], provided the binary separation is large enough so that no mass transfer occurs. If the neutron star fills its Roche lobe, any further decrease in separation will produce mass transfer, which can be stable or unstable, depending on the initial mass ratio. We study the coalescence of the binary by performing dynamical runs starting with initial configurations that are on the verge of initiating mass transfer.

High mass ratios

For an initial mass ratio of unity, the neutron star overflows its Roche lobe at a separation $r = 2.78R_{NS}$ (the orbital period at this separation is 2.3 ms). A very fast episode of mass transfer ensues, in which $0.9 M_{\odot}$ are accreted by the black hole (Figure 1). Note that we have not included a gravitational backreaction force in our

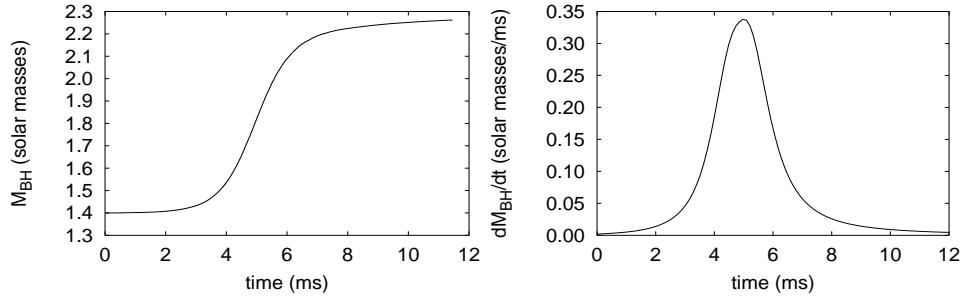


FIGURE 1. Black hole mass (left) and accretion rate onto the black hole (right) for an initial mass ratio of $q = 1$ in a tidally locked binary.

calculations, but the orbital decay is driven by hydrodynamical effects which are comparable in magnitude to angular momentum losses to gravitational radiation. We observe the formation of a transient accretion torus (Figure 2) containing about 0.1 solar masses around the black hole, lasting for several orbits. To the limit of our resolution ($10^{-4} M_{\odot}$), there is a baryon-free axis along the rotation axis of the binary throughout the simulation. We are unable at present to follow the further evolution of the matter spread around the black hole for more than 11 ms. Note

that the neutron star is not completely disrupted by the initial encounter, but that a low-mass core survives and is transferred to a higher orbit by conservation of angular momentum. This core contains approximately 0.43 solar masses, and thus the final mass ratio in the binary is $q = 0.19$, while the separation has increased to about 47 km.

Lower mass ratios

We have also investigated the outcome of a coalescence for lower mass ratios, i.e. with a more massive black hole. For an initial mass ratio of $q = 0.31$, corresponding to a black hole mass of $4.5 M_{\odot}$, the evolution of the binary is quite different than that presented above. The separation corresponding to the onset of mass transfer is $r = 50.4$ km, but for this case the neutron star is not violently disrupted. Instead, mass transfer through Roche-lobe overflow occurs, with about 1% of the mass of the neutron star being transferred to the black hole. The binary separation increases slightly (Figure 3), and the whole episode conserves total orbital angular momentum. All the matter stripped from the neutron star is accreted by the black hole, hence no torus forms, and a baryon-free axis is also present. However, the mass transfer episode lasts about 11 ms, and angular momentum losses to gravitational radiation cannot be ignored. Also, the assumption of tidal locking is not thought to be realistic [1].

Binaries which are not tidally locked

Suppose we now remove the restriction of tidal locking. If the neutron star is initially spherical and non-rotating, the presence of the black hole will create a tidal bulge on the neutron star. The neutron star will then be spun-up to some degree, and this spin angular momentum will be extracted from the orbital component. The orbit will thus decay on a shorter time scale. We have performed just such a calculation, starting with an initial mass ratio of $q = 0.31$ as above, and with a neutron star that is initially spherical and not spinning. The orbital evolution is now much more rapid, with an episode of mass transfer lasting less than 4 ms (Figure 4). The total mass transferred is $0.6 M_{\odot}$, and again the core of the neutron star ($0.8 M_{\odot}$) is not disrupted, but transferred to a higher orbit. The final separation is approximately 70 km.

DISCUSSION

Our simulations [3,6] lead us to believe that for the equation of state used here the survival of the neutron star core is a robust result. The timescale for the entire coalescence is thus lengthened from a few milliseconds to at least several tens of milliseconds, since a binary with a lower mass ratio and greater separation (the

result of the initial episode of mass transfer) will take a longer time to decay via angular momentum losses to gravitational radiation. Furthermore, to the limit of our resolution, there is a baryon-free axis along the rotation axis of the binary present throughout the simulation in every case. Calculations with improved resolution are required to determine if the baryon loading is low enough to accomodate the requirements of the blast-wave model for GRBs [7].

We note that without the formation of a torus, it is difficult to extend the time scale of the coalescence to many seconds, but we nevertheless believe that the coalescence of a neutron star with a black hole is a promising candidate source for the central engine of the shorter gamma ray bursts in the bimodal distribution [4].

These results also suggest that black hole-neutron star binaries might well be the production sites for low-mass neutron stars unstable to explosion. The details of how the remnant core would react to the violent episode of mass loss depend on the equation of state, but it has been shown [2,11] that if the mass were to drop below the minimum required for stability, a violent explosion would ensue. The timescale for this event is not certain, but estimates range from a few milliseconds to several tens of seconds.

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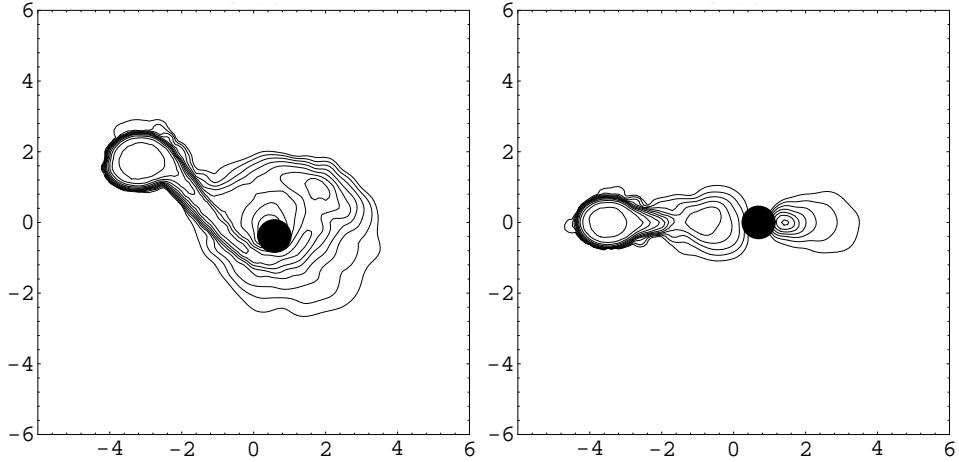


FIGURE 2. Density contours for the initially tidally locked binary with $q = 1$ in the orbital plane (left) and a meridional plane (right). Orbital rotation is counterclockwise. There are eleven evenly spaced logarithmic contours between 5×10^{14} kg m $^{-3}$ and 5×10^{17} kg m $^{-3}$. The axes are labeled in units of R_{NS} .

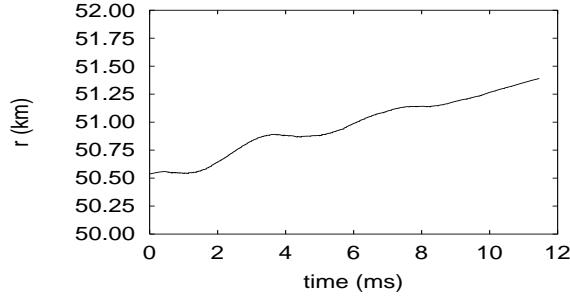


FIGURE 3. Binary separation r as a function of time for an initially tidally locked binary with an initial mass ratio of $q = 0.31$.

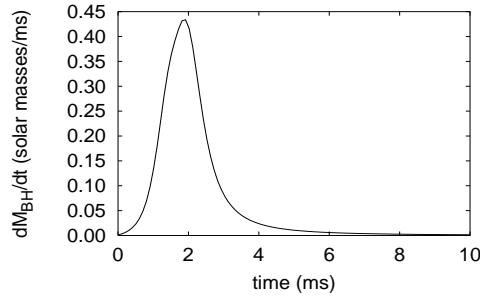


FIGURE 4. Mass accretion rate onto the black hole for a binary with an initial mass ratio $q = 0.31$ that is not tidally locked (the neutron star is initially not spinning).